SOIL SOLARIZATION WEED CONTROL IN SPECIALTY CROPS

BY

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THESIS

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Abstract

Soil solarization (SS) is a broad-spectrum soil disinfestation technique for the control of crop diseases, nematodes and weeds. Target soils are tilled, irrigated to field capacity, covered, and sealed with transparent polyethylene (PE) plastic mulch during the hottest part of the year for a period of 4-6 weeks. Applied water in soil micropores is heated by high ambient temperatures and solar radiation, creating a "greenhouse effect" under plastic, resulting in temperatures lethal to dormant seeds of many weed species.

Recent increases in demand for organic farm products dictates a need for effective, non-chemical weed control strategies, such as SS. Adoption of solarization in the US has been sporadic, though several studies have been conducted on its weed-control potential. Results suggest that conditions for successful weed control via SS may be met in the Midwest. However, SS has not been thoroughly evaluated as an integrated weed management tactic in the Midwest, so its feasibility in the region is unknown.

In 2018 and 2019, we evaluated the effectiveness of one month of SS as a weed-control technique for fall-season vegetable production, as well as significantly shorter SS periods and effects of a biochar amendment prior to plastic coverage. We also defined parameters for determining successful days of SS. One month of SS with two different single-layer clear PE plastics reduced estimated weed coverage and number of weeds m^{-2} by 95% and 75%, respectively. Subsequently, we observed no significant difference in weed control by SS with 66-74% shorter SS application times. Where applied, biochar amendments significantly reduced weed biomass. Results suggest that SS with clear PE plastic is an excellent weed control strategy that is well suited to Midwest fall vegetable production.

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CHAPTER 1: SOIL SOLARIZATION

Soil solarization (SS) is a pre-plant soil disinfestation method that utilizes transparent polyethylene (PE) plastic mulch in an attempt to eradicate, or drastically reduce, existing soil inoculum, crop pests, dormant weed seeds, and existing weed seedlings (Katan 1981). Prior to solarization, the target area is tilled, irrigated to field capacity, covered with PE plastic, and sealed with soil. The aim is to create a "greenhouse effect" under plastic, utilizing solar radiation to raise the soil temperature to a sufficient temperature to eradicate target plant pathogens, pests, and dormant weed seeds (Stapleton et al., 1985). The main modes of action are thermal and hydrothermal, where the topsoil and applied soil water are heated via trapped solar radiation (Horowitz 1980). The goal of SS is to achieve a measurable reduction of the target organism(s) for at least one growing season (Grinstein et al., 1979). Soil solarization has also been referred to as plastic or polyethylene tarping or mulching, soil pasteurization, and other terms; the term soil solarization is now widely accepted and used in more recent literature.

1.1 History

The practice of soil solarization (i.e. SS) originated in Israel (Katan et al. 1976; Mahrer, Y., 1979; Horowitz, M., 1980; Katan, J., 1981; Jacobsohn et al., 1980). Initial experiments were carried out by Katan and coworkers between 1973 and 1975 to evaluate the control of fungal wilt (*Verticillium dahliae*, *Fusarium oxysporum*) in eggplant and tomato (Katan et al., 1976). Levels of pathogen reduction of *V. dahliae* and *F. oxysporum* were between 25-95%, weeds were more than 90% controlled, and both crop growth and quality increased. Later research found significant control of *Verticilium* diseases of potato and cotton, (Davis and Sorensen 1986; Pullman et al. 1981), *Rhizoctonia solani* in onion and potato (Katan et al. 1980; Davis and Sorensen 1986), *Phytophthora* disease in bell pepper and *Fusarium* disease in eggplant (Butler et al., 2014). Additionally, control of several species of nematodes in onion (*Pratylenchus terrestris*; Katan et al., 1980) and potato crops (*Pratylenchus penetrans*; Lazarovits et al. 1991) was achieved, confirming solarization's effective control of major soilborne diseases, weeds and nematodes.

Researchers in the 1980s were also specifically interested in SS's non-chemical nature, citing the need to identify weed and pathogen control strategies to replace methyl bromide, a then-popular soil fumigant that has proven to be hazardous to the environment and human health (Katan et al. 1976; Jacobsohn et al. 1980; Rubin and Benjamin 1983).

1.2 Weeds controlled by solarization

Plant-parasitic and annual weed control

In 1977, researchers in Israel initiated a solarization trial for the control of the plant-parasitic weed Broomrape (*Orobanche aegyptiaca*) and other weeds by solarizing for six weeks (Jacobsohn et al. 1980). Soil temperatures as high as 56 C were observed. Immediately after solarization, a carrot crop was planted, and plant-parasitic, summer annual and perennial crop weed presence was measured at harvest. Broomrape was 100% controlled, and 10 other weeds were significantly controlled. In control treatments, carrots were almost completely destroyed by Broomrape. In a separate study, similar near-total control of previously prevalent summer and winter annual weeds such as pigweeds, common purslane, and henbit (*Amaranthus spp., Portulaca oleracea, Lamium amplexicaule L.*) was achieved (Horowitz et al., 1983).

Peachey et al. (2001) conducted a field trial to test potential solarization control of previously buried seeds of annual bluegrass (*Poa annua*), a pervasive winter annual weed in Oregon nurseries and orchards. Annual bluegrass control of 89-100 % was achieved at depths of 0-5 cm using PE plastic for two months. Maximum soil temperatures of 52 and 47 degrees C at 2.5 cm and 5 cm depths, respectively, were observed. Particular susceptibility of winter annual weeds like *P. annua* to SS is consistent with the findings of both Horowitz et al. (1983) and Rubin and Benjamin (1983).

Perennial weed control

Researchers from the University of California, Davis initiated their own solarization trial for the control of three vigorous perennial weeds (Elmore et al. 1993). johnsongrass (*Sorghum halepense*), bermudagrass (*Cynodon dactylon*) and field bindweed (*Convolvulus. arvensis*) are known for their prolific reproduction capacity by rhizomes and/or possessing extremely deep rooting structures, making them difficult to control with SS (Katan et al. 1987). At five California sites over periods of 6-14 weeks, SS was conducted with 1.5- or 2-mil PE plastic. While field bindweed was 27% controlled, johnsongrass and bermudagrass were 85 and 100% controlled in 6 weeks with PE mulch.

Potential perennial weed tolerance to soil solarization

Perennial weeds have not been consistently controlled in other SS (soil solarization) trials. Elmore et al. (1993) achieved higher levels of perennial weed control than Rubin and Benjamin (1983, 1984), who evaluated SS with PE plastic for control of summer and winter annual weeds as well as some perennial species. Rubin and Benjamin (1983) failed to achieve control of any perennial weed species via SS, and the same findings were reported by Horowitz et al. (1983). Elmore et al. (1993) specifically chose areas of California that were notably more temperate than past solarization research in arid climates, owing to field site proximity to the ocean. With multiple previous examples of failure to control perennial weeds via solarization in the literature, the successful perennial weed control results reported by Elmore et al. (1993) are surprising. It is possible that perennial weed species are more susceptible to soil solarization than previously believed, given the right soil and weather conditions, but more research on susceptibility of perennial weeds to control by soil solarization in similar temperate climates is needed to verify these findings.

A large number of diverse weed species have been significantly controlled by soil solarization (Table 1.1). Weed species highlighted in red are weeds that are common in Midwest agricultural production.

1.3 Types of plastic used for solarization

Types of plastic used for soil solarization are typically clear, 1-2 mils in thickness (mil is equivalent to one one-thousandth of an inch; SS plastic thickness referred to as “mils” in most literature) and manufactured from polyethylene (Elmore et al. 1993).

Other plastic types have been evaluated for SS. In 2000, researchers in Italy evaluated solarizing performance of two plastics for fennel and cauliflower production. Black polyethylene (BPE) and clear PE were compared over a six-week solarization period (Campiglia et al., 2000). Maximum soil temperatures were highest under PE plastic, between 47 and 55 C in the top 5 cm of soil, translating to a 92% and 93% reduction in both weed biomass and weed density, respectively.

In another study (Candido et al., 2011), one month of SS with ethylene vinyl acetate or low-density polyethylene resulted in weed biomass and weed number reductions of 80% in open field and 87% in greenhouse. Although ethylene-vinyl acetate produced marginally higher weed control results, the researchers concluded that low-density polyethylene may be the best choice for specialty crop production, citing its durability and lower cost compared to other plastics. Researchers in Italy concluded that the best-performing SS plastic material was transparent, low-density polyethylene agricultural plastic, previously referred to as PE, CPE or LDPE, (hereafter referred to as PE) (Campiglia et al. 2000; Candido et al. 2011).

Thermal infra-red (TIR) plastic

Previous work suggests some weed species are capable of escaping control by soil solarization with LDPE plastic (Rubin and Benjamin 1984; Anzalone et al. 2010). One specialized SS plastic that could control even the most vigorous weeds is a transparent PE mulch with a thermal infrared-retentive coating applied to one side (referred to as TIR). Chase et al. (1999a) attempted to identify temperature mortality thresholds of yellow and purple nutsedge tubers (*Cyperus esculentus*, *Cyperus rotundus*) using various LDPE plastic treatments and 0.1 mil TIR plastic. Soil solarization weed control activity of thermal infrared retentive (TIR) film was significantly better than with TPE plastic. Researchers reported more than 90% thermal kill of nutsedge tubers in TIR treatments for all subsoil tuber planting levels (5, 10 and 15cm depths) (Chase et al. 1999b). This was the first published solarization study where plastic with a thermal infrared-retentive coating was used to trap long-wave infrared radiation, which can significantly increase soil temperatures compared to typical PE plastic without such a coating.

1.4 Requirements for soil solarization success

Soil moisture as related to hydrothermal soil heating and weed seed dormancy

One of the most critical aspects of successful SS is the initial irrigation event to field capacity described and recommended by Katan (1980) in SS site preparation. Buildup and distribution of hydrothermal heat depends on sufficient soil moisture in the top layer of the soil profile during the active SS period (Rubin and Benjamin 1984). In literature where dry SS treatments were included, pre-irrigated treatments consistently demonstrate increased levels of weed control (Horowitz and Taylorson (1983). Chase et al. (1999b) reported similar results. In their research, high heat treatments on dormant seeds in dry soil did not destroy the seed but weed seed destruction was achieved when adequate soil moisture was present.

The right time of year for soil solarization

If SS is not initiated during the most ideal part of the growing season, then it will be less effective or even ineffective as a weed control strategy in regions where it could be successful. Samtani et al. (2017) conducted SS studies in Virginia in 2013 and 2014, in which SS treatments began in mid-August through early September and continued for 4 or 6 weeks, lasting until mid-October in some cases. There is consensus in the literature that to achieve successful pre-plant weed control via SS, researchers and producers must "solarize" during the part of the local growing season with highest ambient temperatures and solar radiation (Katan et al. 1980; Horowitz, M. 1980, Rubin and Benjamin 1984; Standifer et al. 1984; Chase et al. 1999). Though Samtani et al. (2017) reported a reduction in weed density with SS, their late application of plastic likely resulted in less weed control than may have been observed with an SS period of early July to early August, when solar resources and ambient temperatures are highest.

Combining ideal study conditions with the right plastic: thicker plastic?

Even when ideal SS conditions are present, there are weed species that in past research have proven difficult to control under optimal environmental conditions for SS; purple and yellow nutsedge are examples of weeds previously identified in the literature as species that were particularly resistant to SS (Egley 1983; Rubin and Benjamin 1984; Elmore et al. 1993) because of their deeper roots, storage organs, and occasional ability to penetrate solarization plastic upon germination (Egley 1983; Standifer et al. 1984). However, *Cyperus* spp. were effectively controlled in Brazilian soil solarization studies using thicker-than-average polyethylene plastic (Marenco and Lustosa, 2000). This suggests that there is a potential combination of specialized solarization plastic and optimal environmental conditions (consistently high solar radiation, soil moisture and ambient air temperatures) that could result in solarization's effective control of even the most recalcitrant weed species.

Lethal temperatures

A study was undertaken to identify the simulated SS effects of four high temperatures on the survival and germination of the seeds of eight different weed species in wet or dry soils (Egley 1990). Diurnal variation of solar radiation and soil pulse heating effects were simulated in a laboratory with temperature treatments of 40-70 C of either constant or diurnal heat for periods of 0-7 days.

Dormant weed seeds of all species were extremely tolerant to temperatures as high as 60 degrees C for 7 days in dry soils (Egley 1990). Conversely, a combination of moist soil conditions and 6-hour diurnal temperature pulses between 50 and 60 C achieved 18-100% and 70-100% seed kill, depending on weed species, after 5 days. These results are in agreement with findings of Chase et al. (1999b), who, in a laboratory study, identified 55 degrees C in moist soil for six hours as being lethal even to yellow and purple nutsedge tubers.

The 50-60 C temperature lethality range reported above is significantly higher than weed seed mortality thresholds of 40-45 C reported for common weed species over several weeks in solarization field conditions (Horowitz and Taylorson 1983; Egley 1990; Katan et al. 1987). This research suggests a target temperature range under PE plastic during SS of between 40-60 C to achieve significant control of many winter annual, summer annual, and perennial weeds with optimal soil moisture levels, and with decreasing time required to control with higher temperatures.

Soil albedo and potential solarization soil temperature increases

The effect of soil heating from absorbed solar radiation is well-established in the literature (Katan et al. 1976, 1981; Horowitz 1980; Rubin and Benjamin 1984). However, less well known is to what extent soil albedo can impact soil heating potential. Some work has been done to evaluate the effect of soil albedo (defined as the incidence of solar radiation absorption or reflection on a scale of 0-1) as a contributing factor to the success of SS in lighter-colored, sandy soils in Turkey (Oz 2018). Difference in SS performance was measured in soils with a biochar amendment at a rate of 150 g m^{-2}, and control plots with no biochar application. Significant increases in soil temperature during SS were achieved in plots where biochar was applied. It is thought that light-colored soils amended with biochar can absorb more solar radiation under PE plastic, translating to a decrease in soil albedo and an increase in soil temperature. It is unclear whether high organic-matter soils like those found in central Illinois could experience SS performance benefit from biochar application, since high organic matter typically confers a darker color profile (Baumgardner et al. 1986).

1.5 Solarization treatment length

A broad range of effective SS periods of between 2-14 weeks have been reported in the literature. However, the majority of SS trials used periods of 4-6 weeks. Conversely, several authors utilized periods of two months or longer (Grinstein et al. 1979; Horowitz 1980; Rubin and Benjamin 1983; Porter and Merriman 1983). A surprising number of studies reported solarization periods greater than one month (4-5 weeks: Rubin and Benjamin 1983; 8 weeks: Al-Masoom et al. (1993); and more than 8 weeks: Egley 1983; Rubin and Benjamin 1984; Elmore et al. 1993; Marenco and Lustosa, 2000; Chase et al. 1999a, respectively).

Notably absent from many solarization publications is any discussion regarding the cost to producers of lost production time during SS application. The common application period of 1-2 months is a significant portion of any growing season in any agricultural environment, and plainly not feasible in more temperate climates with shorter growing seasons. Soil solarization research that has been undertaken in more temperate environmental or simulated laboratory conditions (Egley 1990; Peachey et al. (2001)) have utilized solarization periods as short as 7-14 days. These works have largely reported near-identical weed control potential for shorter solarization periods compared with 6 weeks of solarization or more, given the right environmental conditions.

1.6 Solarization cost and IGR (increased growth response)

Cost-estimates of SS including solarizing plastic material costs, installation, and removal are sparse. However, attempts to quantify the cost of SS applications have been made. Pullman et al. (1984) estimated pre-plant, row-coverage cost of soil solarization in California at US $200-250 per acre, and US $350 per acre for solid, whole field coverage.

SS may result in savings in total weed control costs (Anzalone et al. 2010) and can increase crop yield and quality through the increased growth response attributed to SS (Rubin and Benjamin 1983; Stapleton and DeVay 1984; Lazarovits et al. 1991). Hasing et al. (2004) concluded that yield increases in subsequent lettuce and pepper crops – in addition to cost-savings in weed control tactics – were sufficient to justify the cost of SS plastic treatment, confirming previous findings in the literature (Al-Masoom et al.

1993; Katan et al. 1987). This is consistent with yield increases reported by Stapleton et al. (1984) observed in radish, lettuce and okra crops grown in solarized soils of three different textures, where yields increases were between 1- to 5-fold. More examples of increased growth following SS can be found in Oz et al. (2017), Stapleton et al. (1983, 1985) and Stapleton and DeVay (1984).

1.7 Difficulties of organic weed management in the Midwest

It is known that organic cropping systems increase the complexity of weed management. Many organic farmers in the Midwest named weed control as the largest barrier to successful production (DeDecker et al. 2014). In a survey of 219 organic farmers' integrated weed management (IWM) strategies in the Midwestern United States, the authors found more than 50% of respondents were using ten or more IWM strategies on their farms. IWM encompasses a number of strategies based on specific crop production goals of each individual farmer. The majority of surveyed producers were using a broad mix of control strategies. One of the most widely used IWM practices was mechanical or manual cultivation between crop rows, with many farmers noting that multiple treatments were needed to achieve adequate weed control.

The need for multiple control strategies in one crop presents organic producers with several difficulties. In many instances, farmers are unwilling to buy additional specialized farm implements if they already have an IWM plan that has worked for them in the past (Gage and Schwarz-Lazaro, 2019). Additionally, repeated cultivation treatments decrease the cost-effectiveness of manual weed control to the point of economic non-viability for producers, depending on crop value (DeDecker et al. 2014).

Finally, organic farmers that included mechanical control in their IWM rotation (i.e. between-row cultivators, conventional primary tillage implements, and propane flame-weeders) were hesitant to over-rely on them, for fear of increased greenhouse gas emissions and soil compaction.

Effective, single-treatment weed control strategies for the Midwest are desirable to producers. It is known that weed control tactics that preferentially target weed seeds in the soil seedbank or prevent germination and establishment of weeds are generally more effective in the long-term than controlling established weed populations (Davis, 2006). SS appears to fit these parameters and could be a cost-effective, non-chemical addition to Midwest farmers' IWM options as a pre-plant weed control strategy for fall crops.

1.8 Table

Table 1.1 Weed species listed below are common to Midwest agricultural environments and are reported to have been significantly ($P = < 0.05$) controlled by soil solarization in field or laboratory studies.

Weed species	**Author**
Barnyard grass (*Echinochloa crus-galli*)	Vidotto et al. (2013)
Black nightshade (*Solanum nigrum*)	Vidotto et al. (2013)
Common lambsquarters (*Chenopodium album*)	Anzalone et al. (2010)
Common purslane (*Portulaca oleracea*)	Katan et al. (1980); Horowitz et al. (1983)
Field bindweed (*Convolvulis arvensis*)	Candido et al. (2011)
Goosegrass (*Eleusine indica L.*)	Standifer et al. (1984)
Johnson grass (*Sorghum holopense*)	Egley (1983); Rubin and Benjamin (1984)
Large crabgrass (*Digitaria sanguinalis*)	Anzalone et al. (2010)
Prostrate pigweed (*Amaranthus blitoides S. Wats)*	Al-Masoom et al. (1993)
Purple nutsedge (*Cyperus rotundus*)	Marenco and Lustosa (2000)
Redroot pigweed (*Amaranthus retroflexus*)	Candido et al. (2011); Vidotto et al. (2013)
Yellow nutsedge (*Cyperus esculentus*)	Marenco and Lustosa (2000)

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CHAPTER 2: SOIL SOLARIZATION WEED CONTROL IN SPECIALTY CROPS

2.1 Abstract

Control of weed populations in the Midwest continues to be a challenge for organic and conventional vegetable and specialty crop growers. In tandem, consumer interest in organic farm products dictates a need for an effective, non-chemical weed control strategy for producers. We evaluated the effectiveness of one month of soil solarization (SS) as a weed management technique for fall season vegetable production in 2018 and 2019. In 2019 only, we evaluated the impacts of shorter than average SS treatment times and biochar application on subsequent soil temperatures and levels of weed control. Treatments consisted of transparent PE (polyethylene) plastic mulch augmented with several additional treatments. Following SS, carrots (*Daucus carrota subsp. Sativus var. Bollero*) were planted and weed pressure measurements were recorded during crop lifecycle. In 2018 and 2019, maximum soil temperatures achieved were above 50 C. Plots solarized with a 4-mil infrared-retentive (IR) plastic mulch experienced a 90% and 83% reduction in weed coverage and weeds per m^{-2}, as compared to controls. A reduction in SS time of 73% – 8 days instead of 30 – yielded statistically similar weed control results. Biochar applications significantly decreased weed biomass. Carrot yield and quality markedly increased in any plot solarized with clear PE plastic versus black plastic and controls. Soil solarization appears to be an extremely effective pre-plant weed control strategy for Midwest fall-crop production in organic systems and in conventional systems in which herbicide resistance may make weed control difficult.

2.2 Introduction

Soil solarization (SS) is a non-chemical, broad-spectrum soil sterilization strategy for the control of major crop diseases (Katan et al. 1976), nematodes (Heald and Robinson 1987) and weeds (Rubin and Benjamin 1983; Stapleton and DeVay 1986). First pioneered in Israel in the late 1970s and early 1980s (Horowitz 1980; Jacobsohn et al. 1980), it is now a well-known weed control strategy that has been effectively utilized around the world (Mudalagiriyappa and Nanjappa 1999; Katan and Gamliel 2010).

The protocol for conducting SS is simple (Katan 1976; Horowitz 1980); during the hottest part of the growing season, target soils are irrigated to field capacity, covered and sealed with transparent polyethylene (PE) plastic mulch, with the objective being the creation of a "greenhouse effect" under plastic. An application period of 4-6 weeks is suggested (Egley 1983; Rubin and Benjamin 1983; Marenco and Lustosa 2000). The main mode of action of SS is hydrothermal in nature; high ambient temperatures and high levels of incoming solar radiation heat the applied soil water to temperature levels lethal to a broad spectrum of weed species (Stapleton and DeVay 1986).

The implementation of SS in North America has been slow and sporadic, with most SS research and subsequent producer implementation having taken place in California (Stapleton and DeVay 1986; Stapleton 2000) the deep south (Chase et al. 1999; Roe et al. 2004)) and, to limited extent, on the east coast (Samtani et al. 2017) and in the Pacific Northwest (Peachey et al. 2001). However, soil temperatures achieved under SS field conditions in some of these works ranged from 40-55 C or higher, and reported levels of resulting weed control were significant; among weed species significantly or near-completely controlled with SS were: johnsongrass, tall morningglory, purple nutsedge, common lambsquarters, large crabgrass, prostrate pigweed, annual bluegrass, barnyardgrass, common purslane, and chickweed.

Recent economic data from the Leopold Center for Sustainable Agriculture demonstrates an increasing demand for organically produced fruits and vegetables in all major metropolitan areas of the Midwestern region (Swenson 2011), with demand predicted to increase three-fold over the next two decades. However, lack of successful, affordable IWM strategies for organic producers represents possibly the most significant obstacles to meeting this increasing demand (DeDecker et al. 2014). Simultaneously, conventional producers who continue to use herbicides such as glyphosate in their IWM portfolios are encountering agronomic weeds of corn and soybeans that have evolved resistance to between 2-9 herbicide sites of action (SOA), rendering some herbicide products less effective or potentially ineffective for the control of many broadleaf and grass weeds common to the Midwest (United States Soybean Board 2014).

To our knowledge, SS has never been tested as an effective weed management strategy for fall crops in the Midwestern Corn Belt. We propose that one month of SS will provide effective, single-application weed control for Midwest organic producers of fall vegetable crops, and for conventional vegetable crop producers who may be struggling with present or emerging herbicide-resistance in local weed populations. However, the feasibility of SS as a weed control practice for the Midwest is unknown. Also unknown is what type and thickness of PE plastic will generate the best weed control results, or whether augmentation of SS field conditions will be required to achieve satisfactory results.

Until now, nowhere in the literature is there a clear, quantifiable definition of the parameters of a successful day of soil solarization. It is known that soil temperatures between 40-55 C must regularly be reached under solarizing plastic (Egley 1983). It is also known that sufficient soil moisture needs to be present to both conduct hydrothermal heat through soil micropores and increase weed seed susceptibility to thermal inactivation or destruction (Katan 1976; Horowitz and Taylorson 1983; Egley 1990). What is not known, however, is whether soil solarization time of 4-6 weeks is truly necessary. We propose that with adequate soil moisture and high ambient temperatures, control of the large majority of common Midwest weed seed populations should be feasible in a matter of several "solarizing days". It is known that some soil types amended with biochar can be heated to a significantly higher degree via solarization than non-treated soils (Oz 2018). Whether an application of biochar might increase soil temperature in high organic-matter Midwest soils is also unknown.

2.3 Materials and methods

2.3.1 Feasibility and Materials Trial

An experiment was designed to test the solarization potential of several clear polyethylene (PE) agricultural plastic mulches. This study was conducted in 2018 and 2019 on the University of Illinois Sustainable Student Farm in Urbana, Illinois. Soil type in the study area is a Thorp silt-loam soil series (fine-silty, mixed, superactive, mesic, Argiaquic Argialbolls). The experimental design was a randomized complete block with four replications and with a plot size of 1.2 x 4.6 m. In 2018, there were 6 treatments. In 2019, an additional 5 treatments were added (Table 2.1). In 2018 and 2019, SS augmentation treatment consisted of a layer of Tufflite IR plastic covering soil, with a low tunnel of .9m steel bands, and covered by an additional layer of Tufflite IV greenhouse plastic. In both years, 4.6 m by 1.1 m solar reflectors were constructed using steel conduit piping and aluminized PE plastic sheeting for solarization enhancement treatments. Other novel treatments were included in 2019 only. Plastic mulches were manufactured by Berry Global Inc., Evansville, IN, USA (Tufflite products) or by Poly Expert Inc, Laval, Quebec, Canada (Superstrength black plastic products).

Site Preparation

In 2018 and 2019, east-west-oriented rows of raised beds measuring 60.1 x 1.5 m were prepared in late May or late June for July soil solarization. Existing weed stands (majority redroot pigweed, *Amaranthus retroflexus*) were removed manually with stirrup hoes in 2018. Weeds did not emerge between time of raised bed formation and solarization in 2019. Temperature sensors (HOBO® Pendant® Temperature/Light Data Logger UA-002-xx, Onset Computer Corporation, Bourne, MA, USA) were installed at depths of 2.5 and 5.0 cm at two locations in each plot. The temperature sensors were programmed to record soil temperature every 15 minutes. The site was irrigated with overhead sprinklers to field capacity over a 48-hour period prior to plastic installation. Reflector structures were placed on the north-facing side of specific treatments, with aluminized PE plastic reflector faces adjusted to an angle of 90 degrees to reflect maximum sunlight onto double-plastic solarization plots at solar noon.

Solarization

Solarization treatments were installed on 13 July in 2018 and 9 July in 2019 (Table 2.1). Plots were solarized for four weeks. Control plots were not covered, but weeds were manually controlled with stirrup hoes during solarization. Hand-weeded controls were kept weed-free during solarization and then weeded bi-weekly in 2018 and weekly in 2019.

Immediately after SS, all plastic and reflectors were removed, temperature loggers were located and removed, and control plots were manually cultivated, hand-weeded, or flame-weeded according to treatment. Three rows of carrot (*Daucus carota subsp. Sativus, var. Bollero*) were planted on 14 August in 2018 and 9 August in 2019 using a single row push-seeder with 30 cm row spacing. Carrots were irrigated with overhead aluminum irrigation sprinklers (Rain Bird Agri-Products, Azusa, CA, USA) as needed to ensure germination.

Following planting, weed measurements were collected bi-weekly for 10 weeks in 2018 and weekly for 4 weeks then bi-weekly for 6 weeks in 2019. Measurements included percent (%) weed coverage, average number of weeds per m^{-2}, identification of unique weed species present, and tally of total unique weed species identified per plot. These measurements were taken in the center 3.1-m section of each plot. During the eighth week of growth in 2018 and 2019, carrot germination was rated visually on a 0-100 scale. In 2019 only, immediately prior to carrot harvest, aboveground weed biomass was collected from the middle 1.5-m section of each 4.6-m plot, bagged, and oven-dried to measure weed biomass. Weed biomass was not collected in 2018.

Carrots were harvested on 22 October in 2018 and 24-25 October in 2019, using a manual 2-ft wide bed-lifter in 2018, or using a mechanical undercutter tractor implement in 2019. Carrots were harvested from the center 3.1 m of each plot, sorted as marketable and non-marketable, and weighed. Marketable crop carrot crop grade was estimated visually, with slight visual and physical deformities considered marketable. In 2018, full 3.1 m section of harvested carrot was sorted for each treatment. In 2019, because of the much larger quantity of carrot harvested, a 3-kg subsample was taken from each total treatment harvest and sorted as marketable and non-marketable.

2.3.2 Albedo and Timing Trial

An experiment was designed to test how a biochar application or much shorter than average soil solarization times would affect subsequent soil temperatures and weed control results. This study was conducted in 2019 on the University of Illinois Sustainable Student Farm in Urbana, Illinois. Soil type in the study area is mainly a Thorp soil series (fine-silty, mixed, superactive, mesic, Argiaquic Argialbolls).

The experimental design was a two-by-three factorial design with three replications, two levels for biochar amendment (0 = none and 1 = 150 gm m^{-2}), and three levels of solarizing days (1, 2 or 3 days). A control treatment, kept weed-free during SS, was also included. All plastic treatments utilized a 4-mil clear PE plastic with a thermal infrared retentive (IR) coating (manufactured by Berry Global Inc., Evansville, IN, USA). Planting row dimensions and plot size were identical to those in the Feasibility and Materials study discussed above. Biochar application of 150 gm m^{-2} was top-applied evenly across the soil surface of biochar treatments and was not incorporated (Coolterra Products, manufactured by Coolplanet, CO, USA).

Site preparation

Site preparation including soil tillage, bed-shaping, HOBO meter temperature logger installation and field irrigation was identical to protocol outlined for 2018 and 2019 Feasibility and Materials trial. One temperature logger at a single soil depth of 2.5 cm was installed in the center of each treatment. The site was irrigated to field capacity from 7-9 July.

Solarization

We defined the parameters for a successful day of soil solarization as any day when ambient temperatures were above 30 C and when skies were relatively or completely clear. To describe these parameters, we coined the term, “solarizing day” (i.e. SD). We also measured solar radiation (watts/m^{-2}) with a pyranometer (Spectrum Technologies Lightscout Lightmeter, Aurora, IL USA) to better characterize a solarizing day; we averaged radiation readings from 12-4 pm daily.

Solarizing plastic was installed on 9, 11 and 17 July for the 3, 2, and 1 SD treatments, respectively. Conditions were met on 10, 13 and 18 July. All plastic was removed on 19 July after the final solarizing day. Based upon previously described solarizing parameters, SD treatments were under IR solarizing plastic for a total of 1, 8 or 10 total days. All plots were solarized with the same 4-mil, clear PE plastic with thermal infrared retentive (abbreviated IR) coating as in our previous study.

Carrots (*Daucus carota subsp. Sativus, var. Bollero*) were planted on 19 July using a single row push-seeder with a 30-cm row spacing. Three drip-irrigation lines were installed next to planting rows. After one week of drip irrigation, plots were irrigated with overhead irrigation sprinklers as needed (Rain Bird Agri-Products, Azusa, CA, USA).

Germination, weed pressure measurement, and carrot harvest and sorting protocol was identical to protocol described in Feasibility and Materials trial for 2019. However, in this trial, the entire carrot crop was harvested and weighed in this study, as opposed to the 3 m middle section harvested in the previous trial. Carrot crop was harvested on 18 October.

Data Analysis

Treatments in common across study years of Feasibility and Materials trial were analyzed together, and novel treatments used in 2019 only were analyzed separately. Analysis of variance and factorial analysis was performed with JMP®, Version 14. SAS Institute Inc., Cary, NC, 1989-2019. The Tukey-Kramer Comparison test was chosen in both studies to assess significant differences ($P = < 0.05$) between treatments. Soil-temperature measurements in both studies were averaged to identify 4-hour average maximum temperatures during the hottest part of the solarizing day, 2-6 pm.

2.4 Results

2.4.1 Feasibility and Materials Trial

Soil Temperatures

There were significant treatment-by-year interactions for all aspects of our Feasibility and Materials trial results in 2018 and 2019, so data are reported separately for both years. Treatments solarized with clear PE plastic had significantly higher 15-minute and 4-hour average maximum temperatures than did black plastic and control treatments (Tables 2.2 and 2.3). During solarization in 2018 and 2019, clear PE plastic-solarized treatments had 15-minute maximum temperatures that ranged from 51-64 C at 2.5 cm and from 48-61 C at 5 cm. Black plastic maximum temperatures were 43-48 C at 2.5 cm and 42-43 C at 5 cm, while the control maximum temperatures were 41-42 C at 2.5 cm and 39 C at 5 cm, respectively. 4-hour high temperatures under both clear PE plastic treatments regularly exceeded 45 C during one month of SS in 2018 and 2019 (Figures 2.1 and 2.2).

During the four-week solarization periods in 2018 and 2019, 4-hour average maximum temperatures were 44-53 C at 2.5 cm and 41-50 C at 5 cm in treatments when solarized with clear PE plastic (Table 2.3). Four-hour average maximum temperatures for treatments solarized with black plastic were 37-40 C at 2.5 cm and 36-37 at 5 cm. Control treatment had an average maximum temperature of 31-33 C at 2.5 cm and 30-32 C at 5 cm, respectively. Novel single layer, double layer, and control treatments used only in 2019 generated temperatures that were not significantly different from single layer, double layer, and control treatments used in both 2018 and 2019 (Table 2.3).

Days with highest reported average soil temperatures were 17, 18, and 25 July in 2018 and 13, 14, and 19 July 2019. On those three days in either year, average 4-hour maximum temperatures for all solarized treatments were above 50 C at 2.5 cm and 46 C at 5 cm soil depth (data not shown).

Weed Pressure

In 2018 and 2019, there was a significant reduction of percent average weed cover and average number of weeds m^{-2} in any treatments solarized with clear, 4 mil PE plastic compared to control (Table 2.4). Weed population number and plot coverage in plots solarized with black plastic were not significantly different from control treatments in 2018 but were significantly reduced in 2019. Two weeks prior to carrot harvest, percent average weed coverage of plots solarized with clear PE plastic ranged from 3-9% in 2018 and 2-3% in 2019, compared with 18% and 5% cover in 2018 and 2019 for black plastic plots. Comparatively, control treatments were 20% and 35% weed cover in 2018 and 2019.

Average # of weeds m^{-2} for treatments solarized with clear PE plastic ranged from 13-24 weeds m^{-2} in 2018 and from 8-9 weeds m^{-2} in 2019. Treatments solarized with black plastic had 62 weeds m^{-2} in 2018 and 40 weeds per m^{-2} in 2019, and uncovered controls had 76 or 52 weeds m^{-2} in 2018 and 2019. Weed biomass in any treatment solarized with any plastic was significantly reduced compared to flame-weeded and non-flame-weeded controls (Table 2.4).

Across study years, there was an average of 2.4-4 or 1.2-1.7 unique weeds in treatments solarized with clear PE plastic, as compared with an average of 5.6 and 4.6

unique weeds for treatments solarized with black plastic, and 6.5 or 6.2 unique weeds in control plots (Table 2.4). Specific weed species identified per treatment varied widely in both years (data not shown). There was a noticeable lack of several weed species in plots solarized with clear PE plastic during the crop lifecycle, including common lambsquarters (*C. album*), redroot pigweed (*A. retroflexus*), goosegrass (*Eleusine indica)*, barnyardgrass (*E. crus-galli*) and large crabgrass (*D. sanguinalis*) (Table 2.5). However, there were some weed species that escaped control by solarization in both years, including henbit (*Lamium amplexicaule*), hairy vetch (*Vicia villosa*), ivy-leaf morningglory (*Ipomea hederacea*) common purslane (*Portulaca oleracea*) and dandelion (*Taraxacum officinale*) (Table 2.5).

Crop Harvest

There was a range of carrot harvest weights for all solarized treatments from 1.8 to 2.3 kg m^{-2} in 2018 and 2.1-2.3 in 2019, compared with a range of 0.9 to 1 kg m^{-2} in 2018 and 0.5 to 2.1kg m^{-2} in 2019 for control and hand-weeded control treatments, respectively (Table 2.6). In both 2018 and 2019, solarized treatments had significantly higher harvest weight and marketable crop percentage than control treatments. Harvest results for novel solarization treatments in 2019, analyzed separately, were not significantly different from similar solarization treatments across study years (Table 2.6).

2.4.2 Albedo and Timing Trial

Soil Temperatures and Solar Radiation

During solarization, 4-hour average maximum soil temperatures in solarized treatments averaged 15 C hotter than controls (Table 2.7). Neither biochar nor solarizing day had a significant effect on 4-hour maximum soil temperatures in solarized plots, which ranged from 50-53 C. On 10, 13 and 18 July, our conditions were met for being a solarizing day. On designated solarizing days (SD), solar radiation during 12-4pm was above 1000 watts m^{-2}, compared to 859 watts m^{-2} for non-solarizing days of the 9-day study period.

Weed Pressure

There were significant effects of biochar and solarizing days (SD) on weed pressure ratings. In 2 and 3 SD treatments, there was 0-11% plot coverage by weeds over four weed pressure observation dates from 30 July to 25 September, compared to 7-50% plot coverage over the same interval for 1 SD treatments (Table 2.8).

Biochar had a significant effect on percent weed cover for 2 of 4 weed pressure observations from 30 July to 25 September. In plots that received a biochar application, percent weed cover was 2% and 7% for the first two weed observation dates, 30 July and 14 August, compared with 4% and 24% weed cover over the same dates for treatments that did not receive biochar (Table 2.8). Biochar had no effect on weed cover on observation dates of 11 and 25 September. Differences in number of weeds m^{-2} mirrored results of percent weed cover by biochar and solarizing day (data not shown). No differences in number of unique weed IDs were observed between solarized treatments (data not shown).

Weed Biomass and Crop Harvest

Weed biomass was reduced by treatments of 2 and 3 SD compared to 1 SD treatments (Table 2.9). Similarly, treatments that received biochar had reduced weed biomass compared to no-biochar treatments. Carrot harvest weight was increased by 2 and 3 SD treatments compared to the 1 SD treatment (Table 2.9). However, there was no effect of biochar on harvest weight.

2.5 Discussion

2.5.1 <u>Feasibility and Materials Trial</u>

Soil Temperatures

The soil solarization literature shows that soil under plastic must reach temperatures between 40-55 C for a period of several weeks to generate effective, broad spectrum weed control (Katan 1981; Egley 1983; Chase et al. 1999b). The SS augmentation treatment of a double layer of infra-red (IR) and greenhouse PE plastic with a solar reflector gave the best results in terms of both maximum 15-minute and maximum 4-hour average soil temperatures in 2018 and 2019 (Tables 2.2 and 2.3). However, temperatures exceeded the stated 40-55 C target temperature range in all treatments that utilized any amount of transparent PE mulch of 4-mil thickness in both years (Table 2.3).

Although soil temperatures were lower in the single-layer infrared-retentive treatment than in augmentation treatment, they were higher than all other single-layer plastic treatment maximum temperatures at both soil depths – in excess of 43 C in both study years. These results are consistent with findings from Chase et al. (1999a), who reported that IR-retentive PE promoted higher daily maximum soil temperatures than was possible with PE, non-IR PE under field solarization conditions.

In 2018, the soil temperatures above 50 C on 17 and 25 July and on 2 August can be explained by the increase in soil moisture from heavy rainfall on 15, 23 and 31 July, ranging from 0.8-2.3 cm in total precipitation. Because of the creation of raised beds in solarization field trials, there were furrows from excavated and mounded soil alongside treatment rows, which collected rainwater. Subsequent high ambient temperatures on 16 and 24 July and on 1 August and the increased thermal conductivity in soil after re-wetting by rainfall may explain high soil temperatures. Moist soil is more quickly heated than dry soil at shallow depths as a result of increased hydrothermal heat conduction. This is described by Katan et al. (1976) and Egley (1990) in detail. A similar association in peak maximum temperatures after rainfall events did not occur in 2019 as we observed in 2018; however, as previously mentioned, ambient temperatures were not as high in 2019 during the 24-hour periods after rainfall events, and with the exception of 2.3 cm of rainfall on 14 July, rainfall events were not nearly as common or severe in 2019 as they were in 2018.

Results obtained for several 2019 novel treatments showed that the double layer component of our original augmentation treatment was more effective than the use of a solar reflector for raising soil temperatures. The double layer raised maximum temperatures reported by 5 C above single layer IR treatment, versus 2 C as the average increase from solar reflectors, on average (Table 2.3). Results are partially explained by lower ambient temperatures in 2019 than in 2018, and thus a decrease in solar reflector effectiveness. Results of soil temperature differences in 2019 novel irrigated versus non-irrigated treatments are difficult to explain. We expected to see increases in soil temperatures of treatments that received sporadic irrigation in furrow, mimicking field conditions experienced in 2018 that seemed to lead to highest recorded temperatures (Figure 2.3), though we failed to see such results in these treatments. It is possible that too much water was applied, overall, by two irrigation treatments per week. Katan et al. (1976) and Katan (1981) both note that field flooding and standing water for prolonged periods during solarization can decrease effectiveness of weed control. Our results indicate that sporadic re-wetting of soil under plastic may lead to increased soil temperatures by improved heat conduction via increased moisture. However, there is likely a limit to soil moisture that if exceeded, would be a detriment to achieving high solarization temperatures. More research is needed to better define the relationship between high SS temperatures and adequate soil moisture.

Weed pressure

Reported weed control measurements in both study years were very encouraging with respect to the overall question of soil solarization’s feasibility as an effective fall crop weed control strategy for the Midwest. Some of our most exciting results across study years were near-0% plot weed coverage and a 75% reduction in weeds per m^2 in treatments solarized with clear PE plastic compared to control treatments (Table 2.4).

Significant treatment by year interaction can be explained by higher daily maximum ambient temperatures in 2019 in the last three weeks of July compared with the same period in 2018 (data not shown). Frequent instances of single digit percent weed coverage with any clear PE plastic treatments (Table 2.4) are in agreement with results reported by some of soil solarization's early pioneers who reported near-complete weed control of winter and summer annual weeds (Horowitz 1980; Rubin and Benjamin 1984) and difficult-to-control perennial weeds (Katan et al. 1976) using clear PE plastic.

Black plastic decreased all weed pressure measurements compared with controls in 2018, but differences were not significant. We observed significantly improved weed control measures from our black plastic treatments in 2019 in terms of percent weed coverage and number of weeds m^{-2}, though clear PE plastic still yielded significantly improved weed control results (Table 2.4). Black plastic weed control results superior to control plots but inferior to clear PE plastic treatment results are in agreement with previous solarization research comparing clear and black PE mulch performance (Rubin and Benjamin 1983; Horowitz et al. 1983; Samtani et al. 2017). We received black plastic from our farm management staff in 2019, rather than buying our own, so it is possible that although material and thickness of black plastic in 2019 was said to be the same as the previous year, there could have been some slight difference in material and thickness that could explain treatment differences across study years.

Rubin and Benjamin (1983) reported near-complete control of redroot pigweed, common lambsquarters, common purslane, and henbit in areas solarized by clear 1.5 mil PE plastic. With a similar PE plastic, Vidotto et al. (2002) reported near-complete control of large crabgrass, common lambsquarters and barnyardgrass. In our 2018 and 2019 field trials, we achieved the same results with respect to redroot pigweed, common lambsquarters, large crabgrass and barnyardgrass with clear 4 mil PE or IR plastic, confirming SS results of Rubin and Benjamin (1983) and Vidotto et al. (2002) (Table 2.5). In addition, we reported near-complete control of populations of goosegrass (*E. indica*) and green and yellow foxtails (*S. viridis*, *S. glauca*). These results suggest that SS can be an extremely effective tool for combatting problematic weeds in fields of fall vegetable crop producers of the Midwest.

Although common purslane and henbit were among weeds we reported as having escaped control by soil solarization (Table 2.5), infestations generally did not interfere with subsequent carrot crop, and the vast majority of those weeds died when carrot crop closed the canopy over inter-rows and blocked light reception. Presence of these weeds in post-solarization soils is difficult to explain. Rubin and Benjamin (1983) and Horowitz et al. (1983) both reported significant control of small-seeded summer annual as well as winter annual weeds with similar SS plastic, soil high temperatures and application time, so our weed populations of common purslane and henbit should have been controlled but were not. Further research should specifically examine susceptibility of winter annual weeds to control by solarization in the Midwest and explore mechanisms by which these weeds could possibly evade control.

Lack of differences in weed pressure results between 2019 novel treatments and 2018/2019 in-common treatments are not surprising, within view of corresponding reported soil temperature data. There were differences of only 4 C and 2 C between all single layer and double layer treatments, respectively (Table 2.3). Our results suggest that soil solarization with a single 4 mil layer of clear, infrared-retentive PE plastic is sufficient to achieve weed control results comparable to treatments that generated significantly higher soil temperatures without sacrificing additional weed control capacity.

Crop harvest

Carrot was chosen as our study crop because it is known to be an inferior competitor with most weed species (Marenco and Lustosa 2000). Especially in the first several weeks of the crop lifecycle, carrot is especially susceptible to competition by more vigorous weed seedlings, which can result in the death of much of the carrot stand early on. This was the case in our controls in both years (Table 2.6). In surviving carrots harvested from controls, weed pressure damage manifested as stunting and deformation of carrot roots. There was an almost complete absence of weeds in plots solarized with clear PE plastic, so both carrot crop establishment and growth were generally unimpeded for the term of the crop lifecycle where those plastics were applied. Therefore, our harvest results in both 2018 and 2019 (Table 2.6) were not surprising; a significant increase in carrot crop yield and quality was visually evident at the time of harvest in any solarization treatment configuration that used a 4-mil clear PE plastic. In general, this phenomenon closely matched results of previous SS work when researchers used carrot crop as their test crop against the competition of weeds post-SS (Jacobsohn et al. 1980; Marenco and Lustosa 2000).

Marketable percentage of carrot crop was higher in 2018 than in 2019 (Table 2.6). This could be partially explained by the subjective nature of visual carrot marketability sorting protocol used, where the percentage of carrots sorted visually and designated marketable could have varied by year. Yield differences across 2018 and 2019 between single-layer clear PE plastic treatments, though not significant, are disconcerting and are without explanation. Nonetheless, our harvest data suggest that a single weed-control application of soil solarization using 4-mil clear PE plastic was effective at suppressing weeds and helping to produce an excellent yield of high-quality carrot.

2.5.2 **Albedo and Timing Trial**

Soil Temperatures and Solar Radiation

Soil high temperature results observed with the use of 4-mil thermal infrared retentive PE plastic were similar to temperatures observed with the use of similar but thinner infrared retentive plastic in the literature (Chase et al 1999a). Our 4-hour maximum temperature range of 50-53 C over a maximum of 10 days was significantly higher than the same measurement of 44 C over 30 days in our previous solarization trial (Table 2.7 compared to Table 2.3). This confirmed that our outlining of the conditions that should define a solarizing day – as well as the designated dates of 10, 13, and 18 July – correlated well with actual higher than average soil temperatures.

Increases in soil high temperature under solarizing plastic via biochar amendment reported by Oz (2018) were attributed to a lowering of soil albedo and subsequent increase in retention of solar radiation. Turkish soils described in that study were light-colored and sandy in nature, with relatively low organic matter. Our soils are characterized by high clay content and high organic matter. It is disappointing but unsurprising then that our biochar application of 150g m^{-2} (the same as in Oz (2018) did not significantly increase soil high temperatures over treatments without biochar application.

Weed pressure

The tremendous effect of 2 and 3-solarizing day (SD) treatment on percent plot coverage by weeds and weed biomass (Table 2.8) are unsurprising within view of reported 4-hour average high temperatures (Table 2.7), which were at least 50 C. Also unsurprising is the lack of significant difference between 8 and 10 total accumulated days under plastic for these treatments. Conversely, though our 1 SD treatments achieved high temperatures of 50 C, those treatments had weed pressure ratings and weed biomass weights that were not significantly different from controls at the time of harvest (control data not shown). Compared to 1 month minimum of SS suggested in the literature and carried out in our previous trial, 10 or 8 days of solarization represents a precipitous decrease of 66-74% application time. This much shorter but effective solarization application is somewhat supported by Chase et al. (1999a) and Egley (1983, 1990) who reported substantial weed control results from SS simulation studies when heat treatments ranged from several hours to a maximum of only 7 days. Our results indicate that suggested and commonly executed SS periods of 4-6 weeks (Katan et al. 1976; Rubin and Benjamin 1984; Standifer et al. 1984) are potentially far in excess of what is required. Given the right weather conditions, significant weed control via a single SS application was achieved in a fraction of the time previously believed. Future SS research should be conducted in order to confirm our findings regarding the effectiveness of shorter plastic application times determined by our concept of SD.

Significantly improved weed control results seen in treatments with biochar amendments were some of our most difficult results to interpret. 2 and 3 SD treatments had both season-long weed pressure and end-of-season dry weed biomass harvest weights that were significantly reduced where biochar was applied (Tables 2.8 and 2.9). We fail to explain this phenomenon with reported SS soil temperature results, since temperature differences between 2 and 3 SD amended and unamended treatments were 1 C in either case (Table 2.7).

We suggest an alternative explanation, where potential release of VOCs (volatile organic compounds) from our biochar amendment under plastic may have directly or indirectly affected the ability of SS to inactivate or destroy dormant weed seeds. VOCs are known to be released from myriad C-source amendments like biochar after an irrigation event to field capacity and subsequent creation of anaerobic soil conditions by plastic tarping (Strauss and Kluepfel 2015). Giagnoni et al. (2019) found significantly higher quantities of several VOCs in soils amended with biochar than in control soils; these VOCs included acetylene, propene, C4 aldehydes, and acetone. Several of these VOCs have also been correlated to lower soil pH (Momma et al. 2006). Therefore, it is possible that our wetted and heated biochar amendment could have released certain VOCs that altered the soil chemical environment to the point where dormant weed seeds in soil were more susceptible to physical destruction by chemical and SS activity. This is supported by the fact that we did not incorporate our biochar amendment, but top-applied it to the soil surface, rendering it easily exposed to applied irrigation water and direct solar radiation under plastic. Though outside the scope of this work, it is possible that soil chemical shifts resulting from biochar application could have indirectly affected weed seed mortality by shifting the soil microbial community to favor soil microbes antagonistic to weed seed dormancy or seed integrity itself (Mowlick et al. 2013). Future research is needed that quantifies and categorizes VOC emission from amendments of biochar under anaerobic soil conditions created by solarization. Further, an understanding of the direct effects those VOCs would have on dormant weed seeds under anaerobic soil conditions would be desirable.

Weed Biomass and Crop Harvest

Treatments of 2 and 3 SD generated excellent weed control results, compared with 1 SD treatments and controls, which were not significantly different from each other. Therefore, carrot crop harvest weight increases in 2 and 3 SD treatments can easily be explained by the significant reduction of treatment coverage by weeds for the duration of the carrot crop lifecycle (Table 2.8). We reported single digit estimated weed coverage in 2 and 3 SD treatments until 25 September, more than 2 months after carrot planting. The crop was able to put its full energy into quality root development instead of competing with weeds for resources. Additionally, because of significantly shorter SS periods in this trial, carrot crop planting occurred on 21 July, well before the planting date of 14 August in our previous SS trial. Our carrot variety (*Bollero*) required 75 days to maturity, which we met in the Feasibility and Materials trial but exceeded by 15 days before harvest in this trial. Our harvest results here indicate that a significant reduction in SS application time can mean significantly increased crop harvest weight via an earlier planting date and more growing time, especially during longer growing days earlier in the season.

Biochar-amended treatments had reduced weed biomass compared to non-amended treatments (Table 2.9). It is possible that those decreases in weed pressure were responsible for the subsequent harvest weight increases in those same treatments for lack of crop competition with weeds. Though this difference was not significant, it represented a 12% average increase in total harvest weight, which would likely be a significant increase to the bottom lines of Midwest vegetable producers. Rawat et al. (2019) notes that biochar has been known to confer increased water retention capacity where applied, and Warnock et al. (2007) concluded that biochar applications can also promote an increase in crop growth-promoting soil mycorrhizal fungi. Future research at the nexus of biochar application, soil solarization and resulting effects on weed pressure, crop growth and soil microbial and chemical activity is merited.

2.6 Conclusions

2.6.1 Feasibility and Materials Trial

Overall, our results of both study years indicate that soil solarization is a simple yet extremely effective weed-control tactic for fall vegetable crops in the Midwest. With daily maximum soil temperatures in excess of 44 C for one month, solarization with a single-layer application of 4-mil clear PE plastic resulted in near-total control of 7 pervasive Midwest weed species. Further, though we reported significantly higher soil temperatures in other SS treatment configurations, there was no significant difference in weed control between single layer PE plastic treatments and others. Our work suggests that SS with clear, single layer PE plastic should immediately be incorporated into the IWM strategy portfolios of Midwest organic fall vegetable crop producers. Additionally, SS could provide the same weed-control results to conventional producers who may struggle with herbicide resistance or desire to reduce inputs.

2.6.2 Albedo and Timing Trial

The results of this study suggest that soil solarization application times previously suggested in the literature are far in excess of what is required for significant weed control results when ideal SS conditions are present. Using a single-layer 4-mil, clear PE plastic with an infrared-retentive coating, we reported near-complete weed control in treatments solarized for 8 or 10 days, decreased from 30 days in our previous work. These results suggest that given the observation of sufficiently hot weather conditions and execution of SS during that time, producers can decrease the previously suggested SS application time of one month by 66-74% without sacrificing weed control. This could significantly enhance the attractiveness and subsequent adoption of SS as an IWM strategy for Midwest producers of fall vegetable crops. Further, treatments solarized with biochar had significantly decreased total weed biomass at the end of the subsequent crop life cycle, suggesting that growers who utilize short-term SS could see enhanced weed control with a topical application of biochar prior to solarization.

2.7 Tables and Figures

Table 2.1 Solarization treatment list for Feasibility and Materials trial for 2018 and 2019 in Urbana, IL. Treatment abbreviations in parentheses are used in subsequent tables. Further treatment summaries are included where needed in parentheses.

Treatment Type
4-mil Tufflite Greenhouse IV (plastic)
4-mil Tufflite Infrared Retentive (IR plastic)
1-mil Super Strength Embossed Black (Black)
Double layer (Tufflite IV over IR) and reflector (double layer plastics + reflector)
Stirrup hoe control (Control)
Hand-weeded control (hand-weeded) (cultivated prior to SS, bi-weekly or weekly hand-weeded)
*Flame-weeded (Flame) (weekly propane flame application during solarization)
*Double layer only (Tufflite IV low tunnel over IR) (double layer plastics)
*4 mil Tufflite IR plus reflector (IR plastic + reflector)
*Tufflite IR plus irrigation (IR plastic + Wet) (irrigated in furrow for 15 minutes bi-weekly with garden hose)
*Tufflight IR plus irrigation and reflector (IR plastic + Wet + reflector) (irrigated in furrow for 15 minutes bi-weekly with garden hose)

* indicates treatments used only in 2019.

Table 2.2 15-minute interval absolute maximum observed soil temperatures (C) at 2 soil depths in solarization treatments used in 2018 and 2019 Feasibility and Materials trial in Urbana, IL. Results are displayed across study year.

	2018		**2019**	
Treatment	**Soil temperature (C)**		**Soil temperature (C)**	
	2.5 cm	**5 cm**	**2.5 cm**	**5 cm**
Plastic	53	48	51	49
IR plastic	54	51	53	50
Black	48	43	43	42
Double layer plastics + reflector	64	61	57	55
Control	42	39	41	39

Table 2.3 Solarization treatment effect on 4-hour average maximum soil temperatures (C) in treatments used in both 2018 and 2019 Feasibility and Materials trial in Urbana, IL. Daily 4-hour time period was 2-6pm, averaged over duration of study month. Results are reported separately by year due to the presence of a significant treatment by year interaction.

Treatment	2018		2019	
	Soil temperature (C)		Soil temperature (C)	
	2.5 cm	**5 cm**	**2.5 cm**	**5 cm**
Plastic	44 c	41 c	44 c	44 c
IR plastic	46 b	44 b	47 b	45 b
Black	40 d	37 d	37 d	36 d
Double layer plastics + reflector	53 a	49 a	51 a	50 a
Control	31 e	30 e	33 e	32 e
			2019 only	
Flame	-	-	35 d	34 d
Double layer plastics	-	-	51 a	51 a
IR plastic + reflector	-	-	48 b	48 b
IR plastic + wet	-	-	46 c	46 c
IR plastic + Wet + reflector	-	-	47 bc	47 bc

Different letters within a column indicate significant differences as determined by Tukey-Kramer multiple comparison test at a rejection level of α=0.05 with Honest Significant Difference (HSD) shown where significance was found.

Table 2.4 Solarization treatment effect on three weed pressure measurements for Feasibility and Materials trial in Urbana, IL. Results are displayed across study year due to a significant year and treatment interaction for in-common treatments in 2018 and 2019. Treatments with asterisks were only applied in 2019. Weed pressure was tracked for 10 weeks post-soil solarization. Results displayed are reported weed pressure levels immediately prior to crop harvest.

Treatment	2018			2019		
	% weed cover	# weeds/m^2	# unique weed IDs	% weed cover	# weeds/m^2	# unique weed IDs
Plastic	9 b	24 b	4 ab	3 b	9 c	1.7 c
IR plastic	5 b	15 b	2.7 b	3 b	7 c	1.5 c
Black	18 a	62 a	5.6 a	5 b	40 b	4.6 b
Double layer plastics + reflector	3 b	13 b	2.4 b	2 b	8 c	1.2 c
Control	20 a	76 a	6.5 a	35 a	52 a	6.2 a
*Flame	-	-	-	36 a	48 ab	5.3 ab
*Double layer plastics	-	-	-	2 b	5 c	1.4 c
*IR plastic + reflector	-	-	-	2 b	7 c	1.2 c
*IR plastic + wet	-	-	-	3 b	5 c	2.0 c
*IR plastic + wet + reflector	-	-	-	2 b	7 c	1.2 c

Different letters within a column indicate significant differences as determined by Tukey-Kramer multiple comparison test at a rejection level of α=0.05 with Honest Significant Difference (HSD) shown where significance was found.

Table 2.5 List of weed species either susceptible to or resistant to control by soil solarization for Feasibility and Materials trial in Urbana, IL. Weed species controlled or not controlled by soil solarization were almost identical across the study year 2018 and 2019, so species results were combined.

Weeds present in control plots, absent in clear PE plastic-solarized plots		**Weeds that escaped control by solarization**	
Common Name	Scientific Name	Common Name	*Scientific Name*
Red root pigweed	*Amaranthus retroflexus*	Hairy vetch	*Vicia villosa*
Common lambsquarters	*Chenopodium album*	Dandelion	*Taraxacum officinale*
Goosegrass	*Eleusine indica*	Henbit	*Lamium amplexicaule*
Large crabgrass	*Digitaria sanguinalis*	Ivyleaf morning glory	*Ipomea hederacea*
Green/yellow foxtails	*Setaria viridis/glauca*	Common purslane	*Portulaca oleracea*
Barnyardgrass	*Echinochloa crus-galli*	-	-

Table 2.6 Solarization treatment effect on yield and percent marketability of carrot crop (*Daucus carrota* subsp. *Sativus* var. Bollero) for Feasibility and Materials trial in Urbana, IL, 2018 and 2019. Results are given by year due to presence of a significant year and treatment interaction.

Treatment	**2018**		**2019**		
	Yield (kg/m2)	**Marketability (%)**	**Yield (kg/m2)**	**Marketability (%)**	**Weed biomass (g)**
Plastic	1.8 abc	80 a	2.1 a	71 a	42 b
IR plastic	1.9 ab	79 a	2.4 a	72 a	20 b
Black	2.2 a	80 a	2.1 a	66 a	80 b
Double layer plastics + reflector	2.3 a	89 a	2.3 a	76 a	25 b
Control	0.9 c	66 b	0.5 b	31 b	511 a
Hand-weeded	1.0 bc	66 b	2.1 a	75 a	-
*Flame	-	-	0.5 c	28 b	697 a
*Double layer plastics	-	-	2.6 a	79 a	26 b
*IR plastic + reflector	-	-	2.6 a	75 a	31 b
*IR plastic + wet	-	-	2.5 ab	72 a	26 b
*IR plastic + wet + reflector	-	-	2.5 ab	70 a	9 b

* Treatments included in 2019 only

Different letters within a column indicate significant differences as determined by Tukey-Kramer multiple comparison test at a rejection level of α=0.05 with Honest Significant Difference (HSD) shown where significance was found.

Table 2.7 Solarization treatment effect on 4-hour averaged maximum soil temperatures (C) observed across factorial treatments of biochar and solarizing day in 2019 Albedo and Timing trial in Urbana, IL.

Treatment	**2.5 cm**
No biochar 1 SD	50 a
No biochar 2 SD	51 a
No biochar 3 SD	52 a
Biochar 1 SD	50 a
Biochar 2 SD	52 a
Biochar 3 SD	53 a
Control	36 b

SD indicates “solarizing day”.

Different letters within a column indicate significant differences as determined by Tukey-Kramer multiple comparison test at a rejection level of α=0.05 with Honest Significant Difference (HSD) shown where significance was found.

Table 2.8 Solarization treatment effect on percent estimated weed coverage by factors of biochar and solarizing day for Albedo and Timing Trial in Urbana, IL. There was a significant date by treatment factor interaction, so results are shown across multiple weed pressure observation dates.

Factor	**Percent Weed Coverage (%)**			
	30 July	**14 Aug**	**11 Sept**	**25 Sept**
1 Solar. Day	7 a	38 a	37 a	50 a
2 Solar. Days	0 b	5 b	9 b	11 b
3 Solar. Days	0 b	3.5 b	7 b	10 b
No biochar	4 a	24 a	20 a	26 a
Biochar	2 b	7 b	15 a	21 a

Different letters within a column indicate significant differences as determined by Tukey-Kramer multiple comparison test at a rejection level of α=0.05 with Honest Significant Difference (HSD) shown where significance was found.

Table 2.9 Soil solarization treatment effect on dry weed biomass and crop yield (*Daucus carrota subsp. Sativus var. Bollero*) by treatment factors of biochar and solarizing day for Albedo and Timing Trial in Urbana, IL.

Factor	**Dry weed biomass (g/plot)**	**Yield (kg/m^2)**
1 Solarizing Day	298 a	2 b
2 Solarizing Days	66 b	4.3 a
3 Solarizing Days	57 b	4.1 a
No biochar	186 a	3.2 a
Biochar	95 b	3.6 a

Different letters within a column indicate significant differences as determined by Tukey-Kramer multiple comparison test at a rejection level of α=0.05 with Honest Significant Difference (HSD) shown where significance was found.

Figure 2.1 Soil solarization treatment effect on 4-hour average maximum reported soil temperatures in Feasibility and Materials trial, Urbana, IL, 2018. Only 2.5cm soil temperature data is shown. Data shown is the maximum average temperature during a daily 2-6pm time window over one month of soil solarization. Treatments shown were repeated in both study years 2018 and 2019.

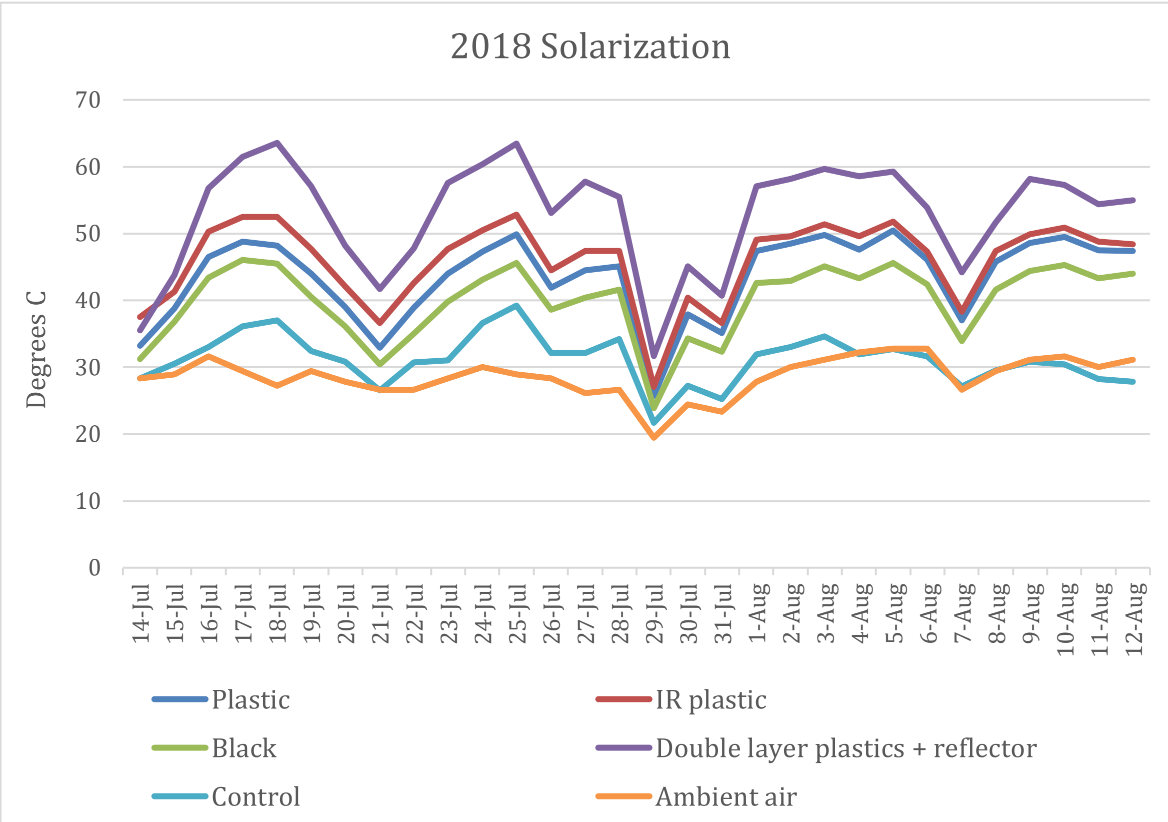


Figure 2.2 Soil solarization treatment effect on 4-hour average maximum reported soil temperatures in Feasibility and Materials trial, Urbana, IL, 2019. Only 2.5cm soil temperature data is shown. Data shown is the maximum average temperature during a daily 2-6pm time window over one month of soil solarization. Treatments shown were repeated in both study years 2018 and 2019.

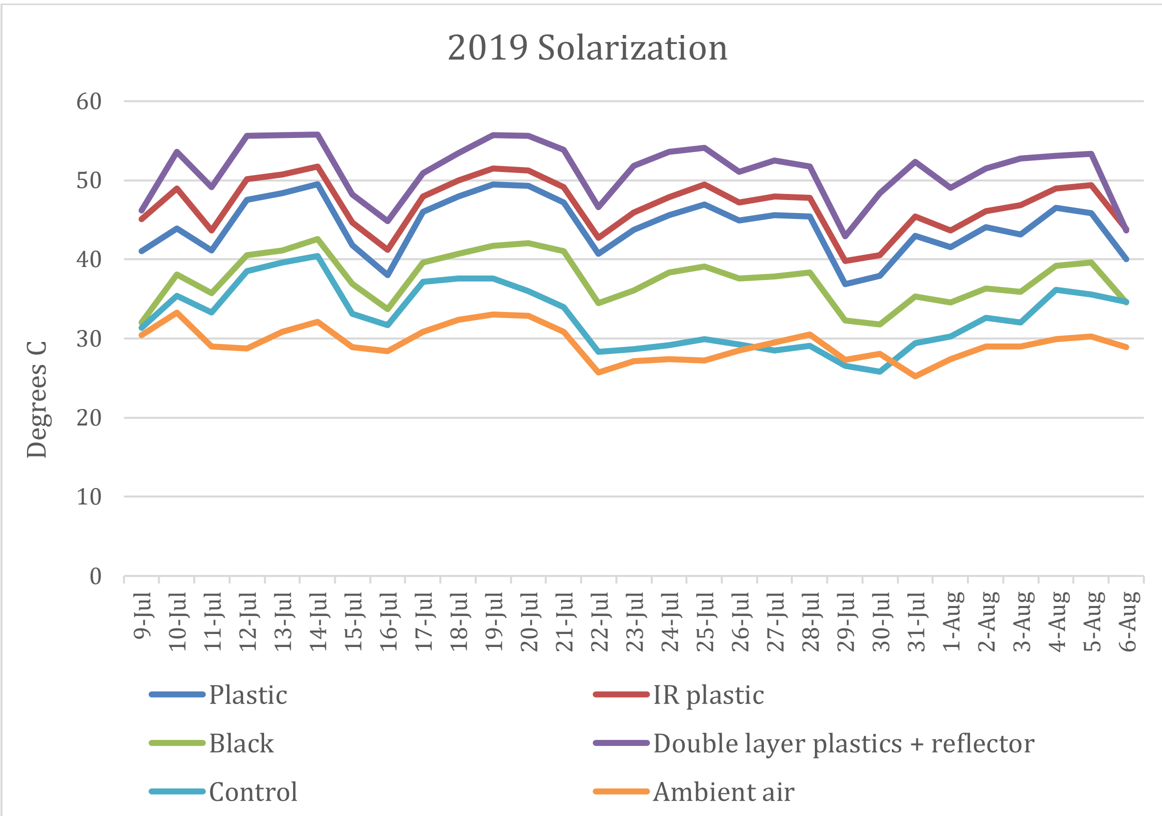
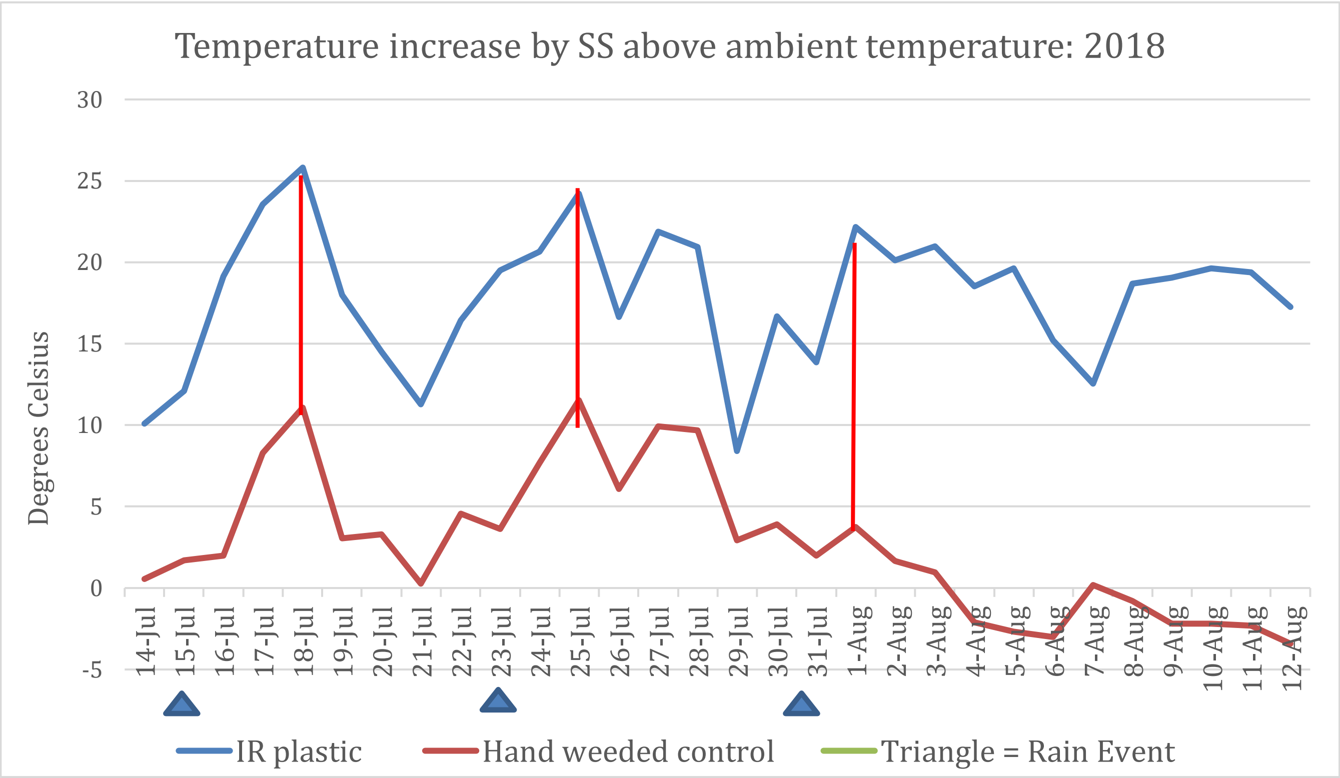


Figure 2.3 2018 increases in temperature resulting from SS treatment of infrared-retentive (IR) plastic, compared to hand-weeded control (HWC) treatment temperature differences from ambient levels. Precipitation events are indicated with blue triangles. Days with the highest measured temperature during one month of solarization are indicated with red vertical lines.



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